CHAPTER 6

Visibility Trends

http://www.epa.gov/oar/aqtrnd98/chapter6.pdf

Introduction

The Clean Air Act (CAA) authorizes the United States Environmental Protection Agency (EPA) to protect visibility, or visual air quality, through a number of programs. These programs include the National Visibility Program under sections 169a and 169b of the Act, the Prevention Of Significant Deterioration Program for the review of potential impacts from new and modified sources, the secondary National Ambient Air Quality Standards (NAAQS) for PM_{10} and $PM_{2.5}$, and section 401 under the provisions for acid deposition control. The National Visibility Program established in 1980 requires the protection of visibility in 156 mandatory federal Class I areas across the country (primarily national parks and wilderness areas). The CAA established as a national visibility goal, "the prevention of any future, and the remedying of any existing, impairment of visibility in mandatory federal Class I areas in which impairment results from man-made air pollution." The Act also calls for state programs to make "reasonable progress" toward the national goal.

In 1987, the Interagency Monitoring of Protected Visual Environments (IMPROVE) visibility network was established as a cooperative effort between EPA, the National Oceanic and Atmospheric Administration, the National Park Service, the U.S. Forest Service, the Bureau of Land Management, the U.S. Fish & Wildlife Service, and state governments. The objectives of the network are to establish current conditions, to track progress toward the national visibility goal by documenting long-term trends, and to provide information for determining the types of pollutants and sources primarily responsible for visibility impairment. Chemical analysis of aerosol measurements provides ambient concentrations and associated light extinction for PM_{10}, $PM_{2.5}$, sulfates, nitrates, organic and elemental carbon, crustal material, and a number of other elements. The IMPROVE program has established protocols for aerosol, optical, and photographic monitoring methods, and these methods are employed at more than 70 sites, most of which are Class 1 areas. In the calendar year 2000, an additional 80 monitoring sites using the IMPROVE aerosol monitoring protocol will be established. The analyses presented in this chapter are based on data from the IMPROVE network, which can be found on the Internet at: **ftp://alta_vista.cira.colostate.edu/DATA/IMPROVE** [1]

This chapter presents aerosol and light extinction data collected between 1989 and 1998 at 34 Class I areas in the IMPROVE network. Because the CAA calls for the tracking of "reasonable progress" in preventing future impairment and remedying existing impairment, this analysis looks at trends in visibility impairment across the entire range of the visual air quality distribution. To facilitate this approach, visibility data have been sorted into quintiles, or 20 percent segments, of the overall distribution, and average values have been calculated for each quintile. Trends are presented in terms of the haziest ("worst") 20 percent, typical ("middle") 20 percent, and clearest ("best") 20 percent of the annual distribution of data. Figure 6-1 provides a photographic illustration of very clear and very hazy conditions at Glacier National Park in Montana, and Dolly Sods Wilderness Area in West Virginia.[2] Figure 6-2 is a map of the 34 Class I areas with seven or more years of IMPROVE monitoring data included in this analysis.

Nature and Sources of the Problem

Visibility impairment occurs as a result of the scattering and absorption of light by particles and gases in the atmosphere. It is most simply described as the haze that obscures the clarity, color, texture, and form of what we see. The same particles

Figure 6-1. Images of Glacier National Park and Dolly Sods Wilderness Area.

Condition:
Bad

Visual Range:
15–25 km

Deciviews:
33–28

Condition:
Good

Visual Range:
150–200 km

Deciviews:
10–7

Condition:
Bad

Visual Range:
<10 km

Deciviews:
>37

Condition:
Good

Visual Range:
80–140 km

Deciviews:
16–10

Glacier National Park **Dolly Sods Wilderness Area**

linked to serious health and environmental effects (sulfates, nitrates, organic carbon, elemental carbon [commonly called soot], and crustal material) can also significantly affect our ability to see.

Both primary emissions and secondary formation of particles contribute to visibility impairment. Primary particles, such as elemental carbon from diesel and wood combustion or dust from certain industrial activities or natural sources, are emitted directly into the atmosphere. Secondary particles that are formed in the atmosphere from primary gaseous emissions include sulfate from sulfur dioxide (SO_2) emissions, nitrates from nitrogen oxide (NO_x) emissions, and organic carbon particles formed from condensed hydrocarbon emissions. In the eastern United States, reduced visibility is mainly attributable to secondarily formed particles, particularly those less than a few micrometers in diameter. While secondarily formed particles still account for a significant amount in the West, primary emissions from sources such as woodsmoke generally contribute a larger percentage of the total particulate load than in the East. The only primary gaseous pollutant that directly reduces visibility is nitrogen dioxide (NO_2), which can sometimes be seen in a visible plume from an industrial facility, or in some urban areas with high levels of motor vehicle emissions.

Visibility conditions in Class I and other rural areas vary regionally across the United States. Rural areas in the East generally have higher levels of impairment than most remote sites in the West. Higher eastern levels are generally due to higher regional concentrations of sulfur dioxide and other anthropogenic emissions, higher estimated regional background levels of fine particles, and higher average relative humidity levels. Humidity can significantly increase the effect of pollution on visibility. Some particles, such as sulfates, accumulate water and grow in size, becoming more efficient at scattering light. Annual average relative humidity levels are 70–80 percent in the East as compared to 50–60 percent in the West. Poor summer visibility in the eastern United States is primarily the result of high sulfate particle concentrations combined with high humidity levels.

Visibility conditions are commonly expressed in terms of three mathematically related metrics: visual range, light extinction, and deciviews. Visual range is the metric best

Figure 6-2. IMPROVE sites meeting data completeness requirements.

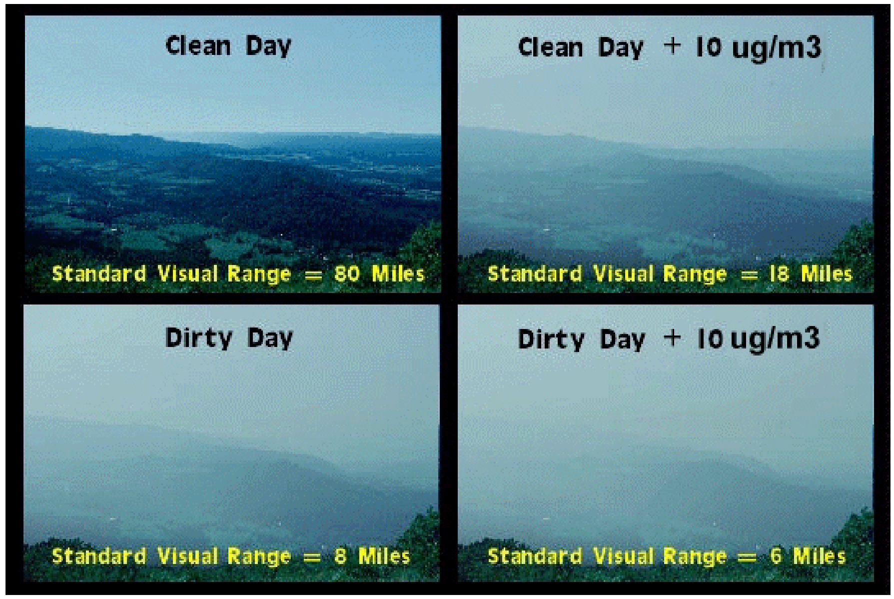
Note: The Washington, DC site is not included in the rural visibility trends analysis.

known by the general public. It is the maximum distance at which one can identify a black object against the horizon, and is typically described in miles or kilometers. Light extinction, inversely related to visual range, is the sum of light scattering and light absorption by particles and gases in the atmosphere. It is typically expressed in terms of inverse megameters (Mm^{-1}), with larger values representing poorer visibility. Unlike visual range, the light extinction coefficient allows one to express the relative contribution of one particulate matter (PM) constituent versus another to overall visibility impairment. Using speciated mass measurements collected from the IMPROVE samplers "reconstructed light extinction" can be calculated by multiplying the aerosol mass for each constituent by its appropriate "dry extinction coefficient," and then summing these values for each constituent. Because sulfates and nitrates become more efficient at scattering light with increasing humidity, these values are also multiplied by a relative humidity adjustment factor.[3] Annual and seasonal light extinction values developed by this approach correlate well with optical measurements of light extinction (by transmissometer) and light scattering (by nephelometer).

The deciview metric was developed because changes in visual range and light extinction are not proportional to human perception of visibility impairment. For example, a 5-mile change in visual range can be either very apparent or not perceptible, depending on the base line level of ambient pollution. The deciview metric provides a linear scale for perceived visual changes over the entire range of conditions, from clear to hazy, analogous to the decibel scale for sound. Under many scenic conditions, a change of one deciview is considered to be perceptible by the average person. A deciview of zero represents pristine conditions.

It is important to understand that the same amount of pollution can have dramatically different effects on visibility depending on existing conditions. Most importantly, visibility in cleaner environments is more sensitive to increases in $PM_{2.5}$ particle concentrations than visibility in more polluted areas. This principle is illustrated in Figure 6-3, which characterizes visibility at Shenandoah National Park under a range of conditions.[5] A clear day at Shenandoah can be represented by a visual range of 80 miles, with conditions approximating naturally-occurring visibility (i.e., without pollution created by human activities). An average day at Shenandoah is represented by a visual range of 18 miles, and is the result of an additional 10 mg/m^3 of fine particles in the atmosphere. The two bottom scenes, with visual ranges of eight and six miles respectively, illustrate that the perceived change in visibility due to an additional 10 mg/m^3 of fine particles to an already degraded atmosphere is much less perceptible than adding this amount to a clean atmosphere. Thus, to achieve a given level of perceived visibility improvement, a large reduction in fine particle concentrations is needed in more polluted areas. Conversely, a small amount of pollution in a clean area can dramatically decrease visibility.

Figure 6-3. Shenandoah National Park on clear and hazy days and the effect of adding 10 $\mu g/m^3$ of fine particles to each.



Long-Term Trends (1970–1990)

Visibility impairment is presented here using visual range data collected since 1960 at 280 monitoring stations located at airports across the country. Trends in visibility impairment can be inferred from these long-term records of visual range. Figure 6-4 describes long-term U.S. visibility impairment trends derived from such data.[4] The maps show the amount of haze during the summer months of 1970, 1980, and 1990. The dark blue color represents the best visibility, and red represents the worst visibility. Overall, these maps show that summer visibility in the eastern United States declined between 1970 and 1980, and improved slightly between 1980 and 1990. These trends follow overall trends in emissions of sulfur oxides during these periods.

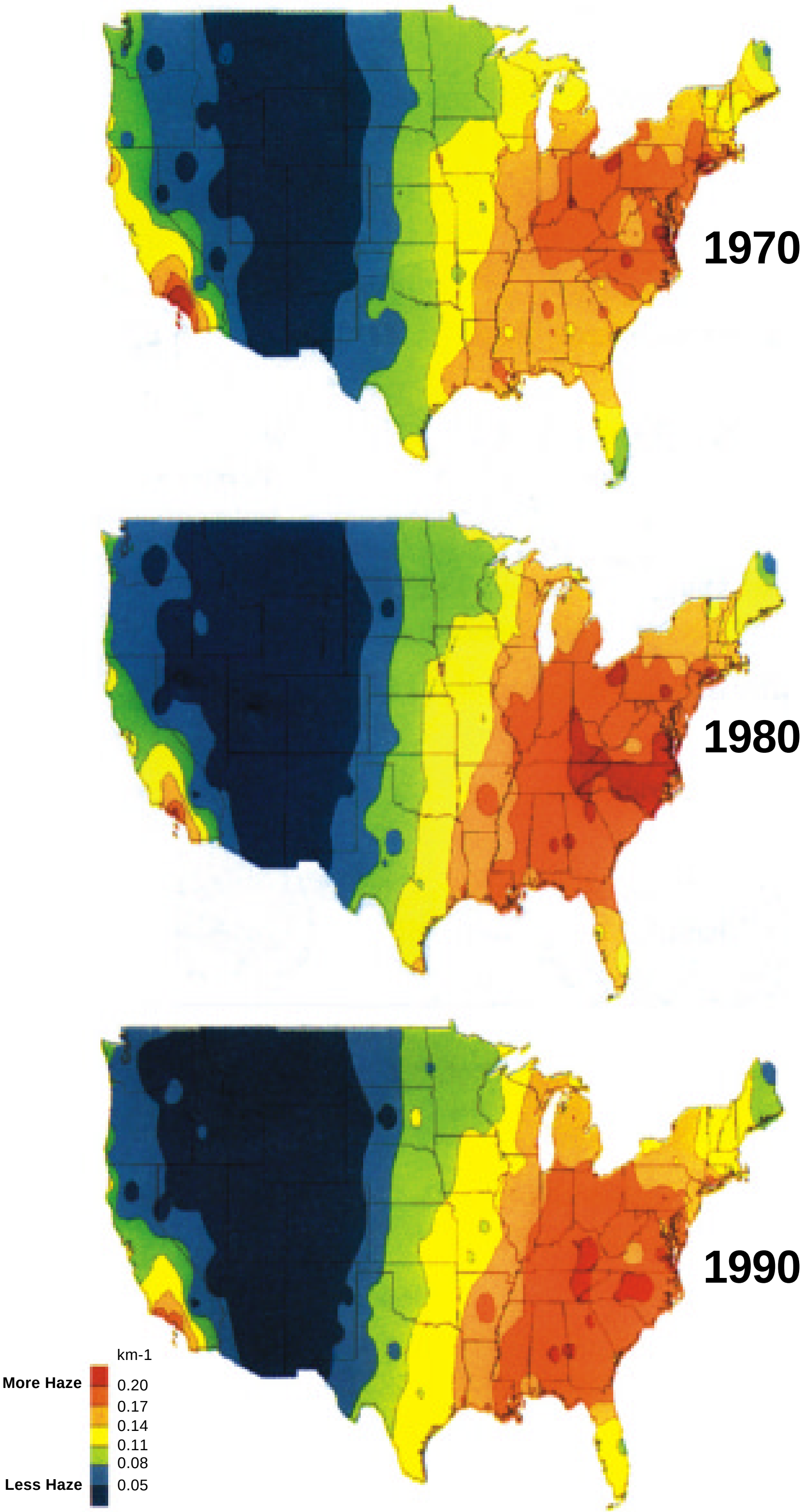
Recent Trends (1989–1998)

Aerosol and light extinction data are presented for 34 sites which produced at least seven years of fine particle data from 1989–1998: 10 are located in the east, and 24 are located in the west, as shown in Figure 6-2. Because of the significant regional variations in visibility conditions, this chapter does not present aggregate national trends, but instead groups the data into eastern and western regions. As noted earlier, trends in this chapter are presented in terms of the annual average values for the clearest ("best") 20 percent, middle ("typical") 20 percent , and haziest ("worst") 20 percent of the days monitored each year. To date, two 24-hour aerosol samples have been taken each week from IMPROVE sites, resulting in a potential for 104 sampling days per year. Beginning in 2000, aerosol samples will be taken every three days, consistent with the approach used for national $PM_{2.5}$ aerosol monitoring.

Regional Visibility Trends for the Eastern and Western United States

Figures 6-5a and 6-5b illustrate eastern and western trends for total light extinction. These figures, presented with equivalent scales, demonstrate the regional difference in overall levels of visibility impairment. For this graph, the light scattering associated with gaseous molecules in clear air is included (known as Rayleigh extinction). One can see that the worst visibility days in the West are only slightly more impaired than the best days in the East. It should also be noted that beginning in 1992, seven additional eastern sites are reflected in Figure 6-5a, bringing the total number of eastern sites reflected in the values plotted in Figure 6-5a for 1992–1998, to 10. By adding the seven eastern sites to the data set, the magnitude of average impairment levels has increased, although the general slope of the trends for clearest, typical, and haziest days appear similar to the trends based on three sites. Figure 6-5a shows that in the East, the haziest visibility days do not appear to be getting any better. Overall, essentially no change in visibility is noted between 1989 and 1998 (based on 3 sites), and a 4-percent degradation occurred since 1992 (based on 10 sites). It is noted that impairment on the haziest days in the East showed modest improvement in 1993. The best visibility days appear to be improving for the three sites over the 10-year period, but show no change since 1992 based on the 10 locations. The typical days (or middle 20 percent of the distribution) show more than a 10-percent visibility improvement for the three sites,

Figure 6-4. Long-term trend for 75th percentile light coefficient from airport visual data (July–September).



and a more modest 5-percent change since 1992 for the 10 sites.

In the West, there appears to be steady visibility improvement for the clearest, typical, and haziest days as presented in Figure 6-5b for the period 1989–1998. Total light extinction for the aggregation of 24 western sites declined by 10–15 percent for each of the 3 categories. This improvement in total light extinction for the worst days corresponds to a reduction of 0.9 deciviews.

The Components of PM Contributing to Trends in Visibility Impairment

The area plots in Figures 6-6a through 6-6f show the relative contribution to aerosol light extinction by the five principal particulate matter constituents measured by IMPROVE at eastern and western sites for the best, middle, and worst 20 percent days. Note that the scale differs for the eastern and western figures in order to more clearly present the relative contribution of the five components. By understanding the total magnitude of each $PM_{2.5}$ component, the change in aerosol composition over time, and the effect of these components on changing visibility, policymakers can design strategies to address health and environmental concerns.

In the East, (Figures 6-6a, b, and c), sulfate is clearly the largest contributor to visibility impairment, ranging from an average of 75–79 percent of each year's annual aerosol extinction during the haziest days to 62–69 percent on the typical days, and to 53–62 percent on the clearest days. Over the 1992–1998 period, the magnitude of aerosol extinction due to sulfates increased, most notably between 1997 and 1998. This change corresponds to the reported increase in sulfate aerosols and summer time increase in regional SO_2 emissions discussed in Chapter 7 (Atmospheric Deposition of Sulfur and Nitrogen Compounds). The organic carbon is the next largest contributor to visibility impairment in the East, accounting for 11–15 percent of annual aerosol extinction on the best days and 10–11 percent on the most impaired days. The third largest contributor in the East is nitrate, which also accounts for about 10–16 percent of annual aerosol light extinction on the best days and about 2–6 percent on the haziest days.

In the West, sulfate is also the most significant single contributor to aerosol light extinction on the clearest, typical, and haziest days. Sulfate accounts for 30–40 percent of annual aerosol light extinction on the best days, 36–44 on the typical days, and 34–41 on the haziest days. However, organic carbon (20–33 percent), crustal material (16–25 percent), and nitrates (7–12 percent) play a more significant role (as a percentage of aerosol extinction) in western sites than eastern ones. Based on this aggregation of 24 sites, the decrease in light extinction noted above can be attributed to downward trends in aerosol elemental carbon and organic carbon. However, carbon increased between 1997 and 1998, offsetting some of these improvements in western Class I areas.

Trends in Specific Class I Areas

IMPROVE data from 34 Class I area monitoring sites[7] were analyzed for upward or downward trends using a nonparametric regression methodology described in Appendix B: Methodology.

Figure 6-5a. Total light extinction trends for eastern Class I areas for clearest, middle, and haziest 20 percent of the days in the distribution, 1989–1998.

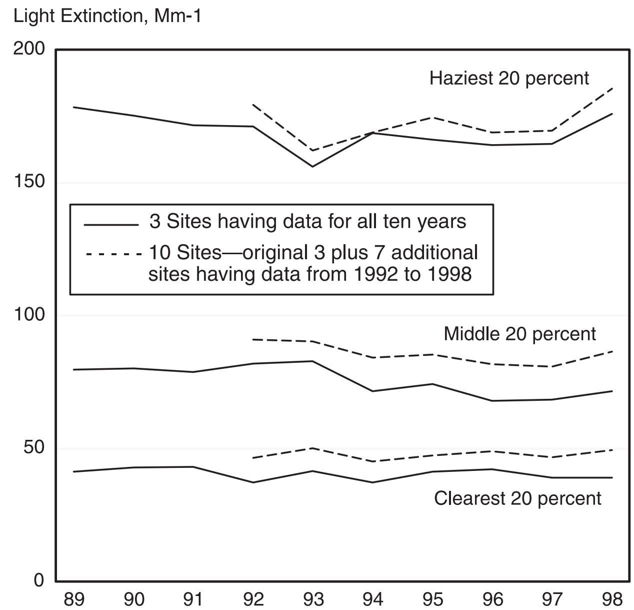
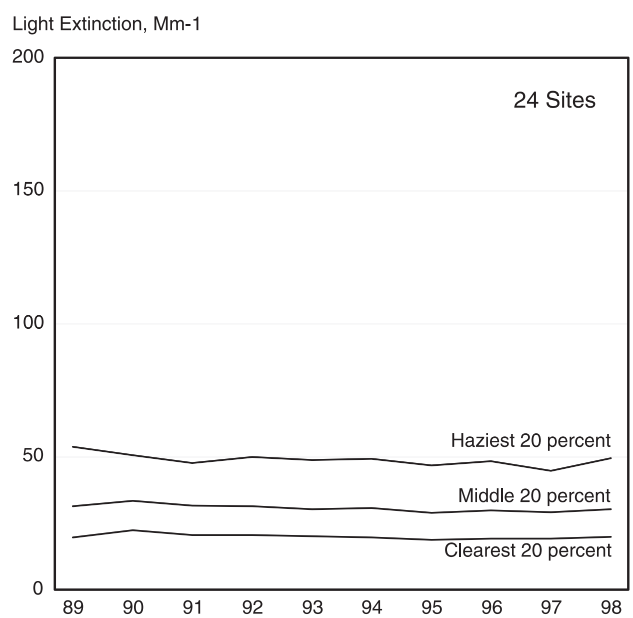


Figure 6-5b. Total light extinction trends for western Class I areas for clearest, middle, and haziest 20 percent of the days in the distribution, 1989–1998.



Note: In the eastern Class I area plots, the 1989–1991 trend is based on the three sites with available data. Beginning in 1992 and going through 1998, there are seven additional sites with trend data.

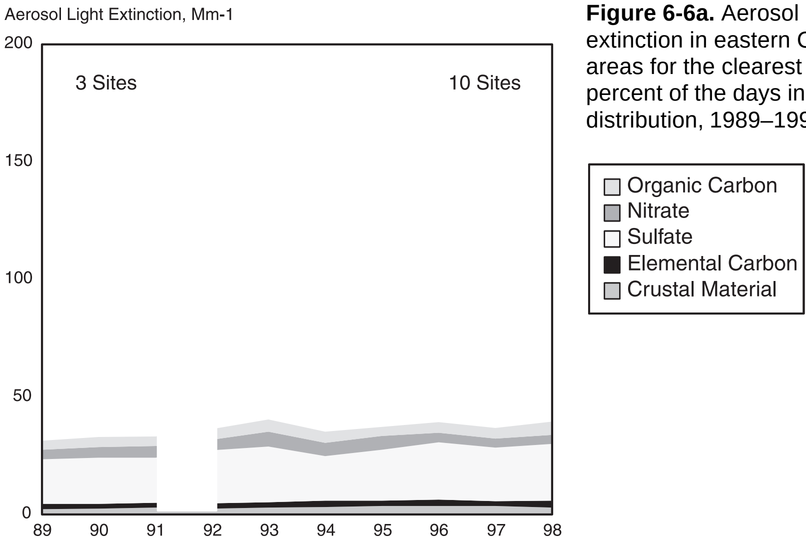


Figure 6-6a. Aerosol light extinction in eastern Class I areas for the clearest 20 percent of the days in the distribution, 1989–1998.

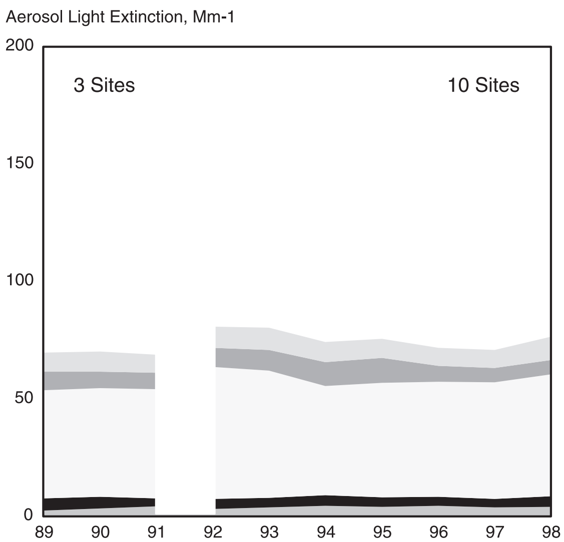


Figure 6-6b. Aerosol light extinction in eastern Class I areas for the middle 20 percent of the days in the distribution, 1989–1998.

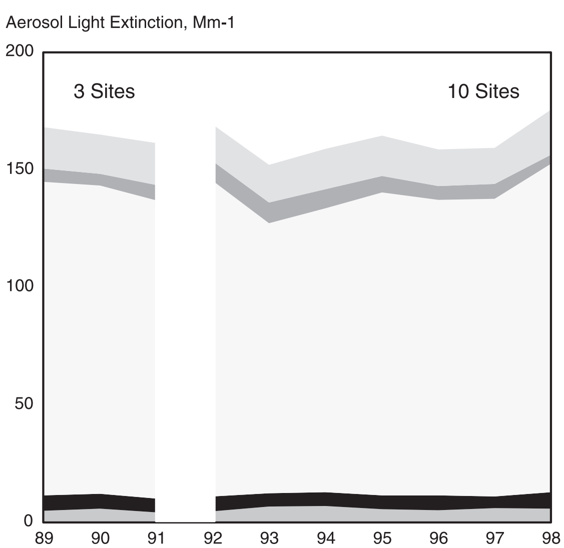


Figure 6-6c. Aerosol light extinction in eastern Class I areas for the haziest 20 percent of the days in the distribution, 1989–1998.

Table 6-1 summarizes the trends analysis performed on these 34 sites for total light extinction (expressed in deciviews) on an area-by-area basis. Four areas in the West showed a significant downward trend in deciviews on the haziest days. However, the 30 remaining Class I areas did not have significant visibility improvement on the haziest days over the 7- to 10-year period.

Current Visibility Conditions

Current annual average conditions range from about 18–40 miles in the rural East and about 35–90 miles in the rural West. On an annual average basis, natural visibility conditions have been estimated at approximately 80–90 miles in the East and up to 140 miles in the West.[4] Natural visibility varies by region, primarily because of slightly higher estimated background levels of $PM_{2.5}$ particles in the East, and the more significant effect of relative humidity on particle concentrations in the East than in the West.

Figures 6-7a, 6-7b, and 6-7c illustrate regional visibility impairment in terms of reconstructed aerosol light extinction based on measurements at IMPROVE sites between 1995 and 1997. Maps are presented for the clearest, typical, and haziest 20 percent of the distribution. The pie

Notes:

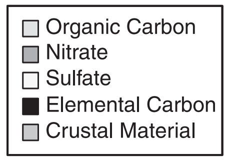
1) To better discern the trend in each component, the vertical scales for the plots of the western Class I areas are smaller than those for the plots of the eastern Class I areas.

2) In the eastern Class I area plots, the 1989-1991 trend is based on the 3 sites with available data. Beginning in 1992 and going through 1998, there are 7 additional sites with trend data.

charts show the relative contribution of different particle constituents to visibility impairment. Annual average aerosol light extinction due to these particles is indicated by the value next to each pie and by the size of each pie.[6] Figure 6-7 also shows that visibility impairment is generally greater in the rural East compared to most of the West. As noted earlier, the pies show that, for most rural eastern sites, sulfates account for more than 60 percent of annual average light extinction on the best days and for more than 75 percent of annual average light extinction on the haziest days. Sulfate plays a particularly significant role in the humid summer months due to its nature to attract and dissolve in atmospheric water vapor, most notably in the Appalachian, northeast, and mid-south regions. The figure also shows that organic carbon and nitrates each account for 10–15 percent of aerosol extinction on the clearest days while elemental carbon only contributes 5–7 percent. On the other hand, organic carbon contributes around 10 percent to aerosol light extinction on the haziest days while nitrates and elemental carbon each typically contribute 2–6 percent.

In the rural West, sulfates also play a significant role, typically accounting for about 30–40 percent of aerosol light extinction on the best days and 35–45 percent on the haziest days. In several areas of the West, however, sulfates account for over 50 percent of annual average aerosol extinction, including Mt Rainier, WA, Redwood National Park, CA, and the Cascades of Oregon. In contrast, it contributes less than 25 percent in southern California. Organic carbon typically makes up 20–30 percent of aerosol light extinction in the rural

Figure 6-6d. Aerosol light extinction in western Class I areas for the clearest 20 percent of the days in the distribution, 1989–1998.



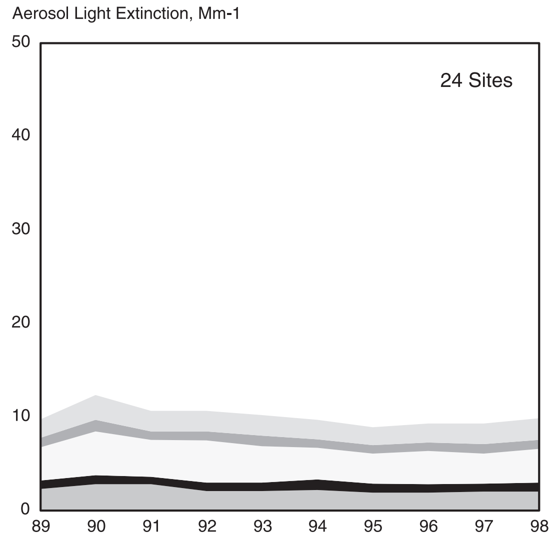


Figure 6-6e. Aerosol light extinction in western Class I areas for the middle 20 percent of the days in the distribution, 1989–1998.

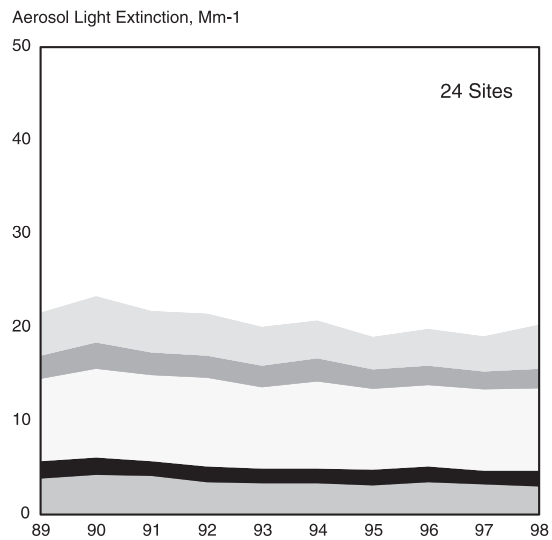


Figure 6-6f. Aerosol light extinction in western Class I areas for the haziest 20 percent of the days in the distribution, 1989–1998.

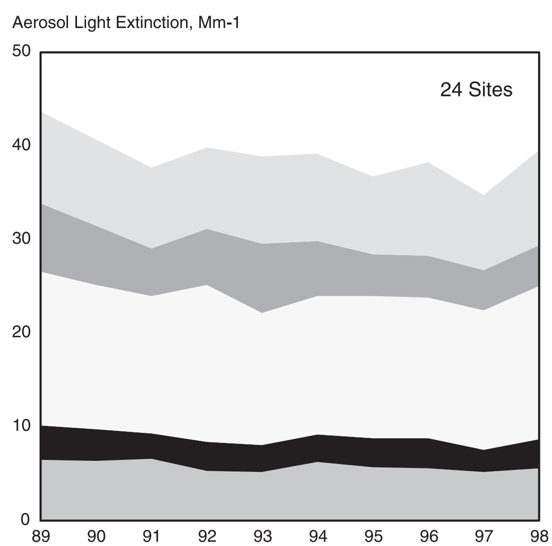


Table 6-1. Summary of Class I Area Trend* Analysis

Parameter	Number of Sites With Significant Upward (*Deteriorating*) Trends		Number of Sites With Significant Downward (*Improving*) Trends	
	West	East	West	East
Deciviews, worst 20%	1	0	4	0
Deciviews, middle 20%	0	0	3	3
Deciviews, best 20%	1	1	5	0
Light extinction due to sulfate, worst 20%	3	0	3	0
Light extinction due to sulfate, middle 20%	2	0	1	3
Light extinction due to sulfate, best 20%	1	0	9	1
Light extinction due to organic carbon, worst 20%	0	0	4	0
Light extinction due to organic carbon, middle 20%	0	0	6	0
Light extinction due to organic carbon, best 20%	3	0	4	0

* Based on a total of 34 monitored sites with at least seven years of data: 24 in the west, 10 in the east.

West, elemental carbon (absorption) accounts for about 10 percent, and crustal matter (including coarse PM) accounts for about 15–25 percent. Nitrates typically account for less than 10 percent of total light extinction in western locations, except in the southern California region, where it accounts for almost 40 percent.

Figures 6-8a, 6-8b, and 6-8c illustrate current levels of visibility impairment, in terms of deciviews, for the clearest, typical, and haziest 20 percent days based on IMPROVE data from 1995–1997.[7] Note that the deciview scale is more compressed than the scale for visual range or light extinction, with larger values representing greater visibility degradation. Most of the sites in the intermountain West and Colorado Plateau have annual average impairment of 12 deciviews or less, with the worst days ranging up to 16 deciviews. Several other western sites in the northwest and California experience levels on the order of 15–25 deciviews on the haziest 20 percent of days. Many rural locations in the East have annual average values exceeding 23 deciviews, with average visibility levels on the haziest days up to 33 deciviews.

Programs to Improve Visibility

In April of 1999, EPA issued the final regional haze regulation.[8] This regulation addresses visibility impairment in national parks and wilderness areas that is caused by numerous sources located over broad regions. The program lays out a framework within which states can work together to develop implementation plans that are designed to achieve "reasonable progress" toward the national visibility goal of no human-caused impairment in the 156 mandatory Class I federal areas across the country.

States are required to establish goals to improve visibility on the 20 percent worst days and to allow no degradation on the 20 percent best days for each Class I area in the state. In establishing any progress goal, the state must analyze the rate of progress for the next 10–15 year implementation period which, if maintained, would achieve natural visibility conditions by 2064. The state will need to show whether this rate of progress or another rate is more reasonable based on certain factors in the Clean Air Act, including costs and the remaining useful life of affected sources. Along with these goals, the state plans must also include emission reduction measures to meet these goals (in combination with other states' measures), requirements for Best Available Retrofit Technology on certain large existing sources (or an alternative emissions trading program), and visibility monitoring representative of all class I areas.

State regional haze plans are due in the 2003–2008 timeframe. Because of the common precursors and the regional nature of the PM and regional haze problems, the haze rule includes specific provisions for states that work together in regional planning groups to assess the nature and sources of these problems and to develop coordinated, regional emission reduction strategies. One provision allows nine Grand Canyon Visibility Transport Commission States (Arizona, California, Colorado, Idaho, Nevada, New Mexico, Oregon, Utah, and Wyoming) to submit initial plans in 2003 to implement their past recommendations within the framework of the national re-

Figure 6-7a. Aerosol light extinction (in Mm^{-1}) for the clearest 20 percent days and contribution by individual particulate matter constituents, based on 1995–1997 IMPROVE data.

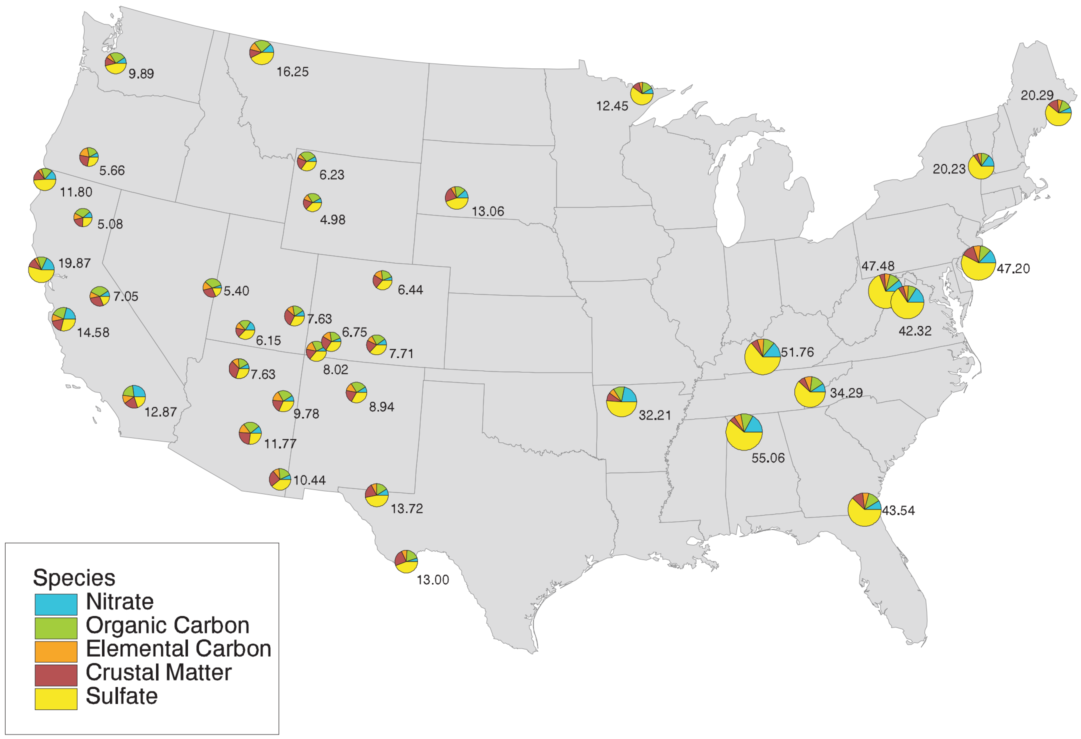


Figure 6-7b. Aerosol light extinction (in Mm^{-1}) for the middle 20 percent days and contribution by individual particulate matter constituents, based on 1995–1997 IMPROVE data.

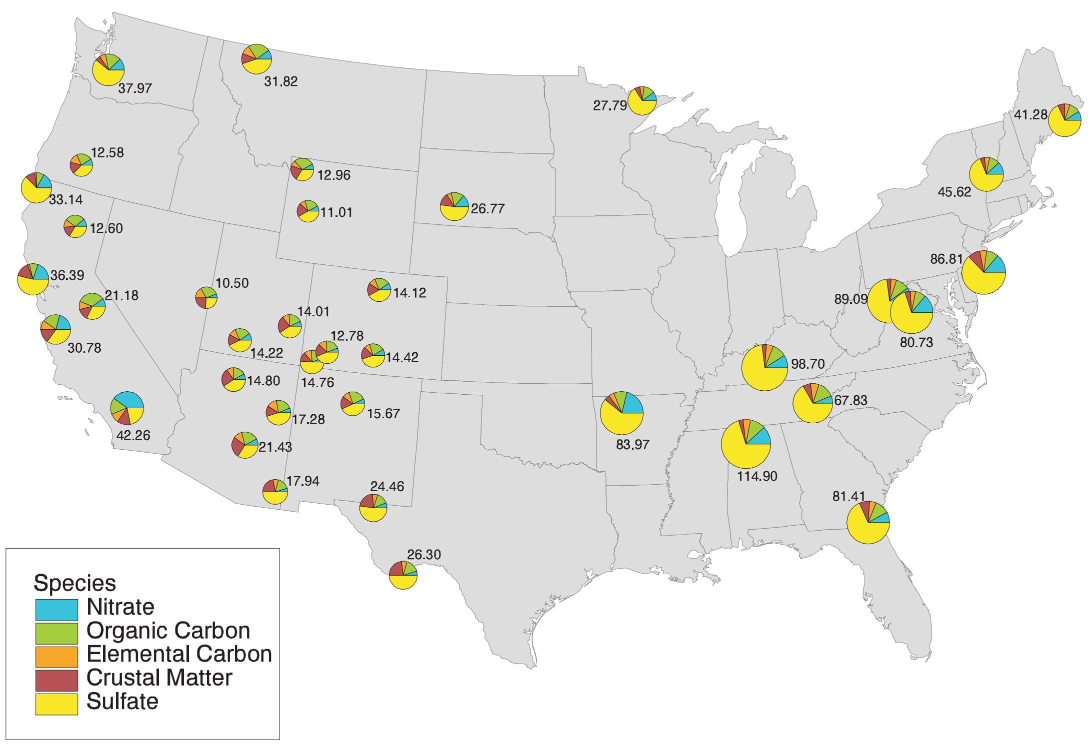


Figure 6-7c. Aerosol light extinction (in Mm^{-1}) for the haziest 20 percent days and contribution by individual particulate matter constituents, based on 1995–1997 IMPROVE data.

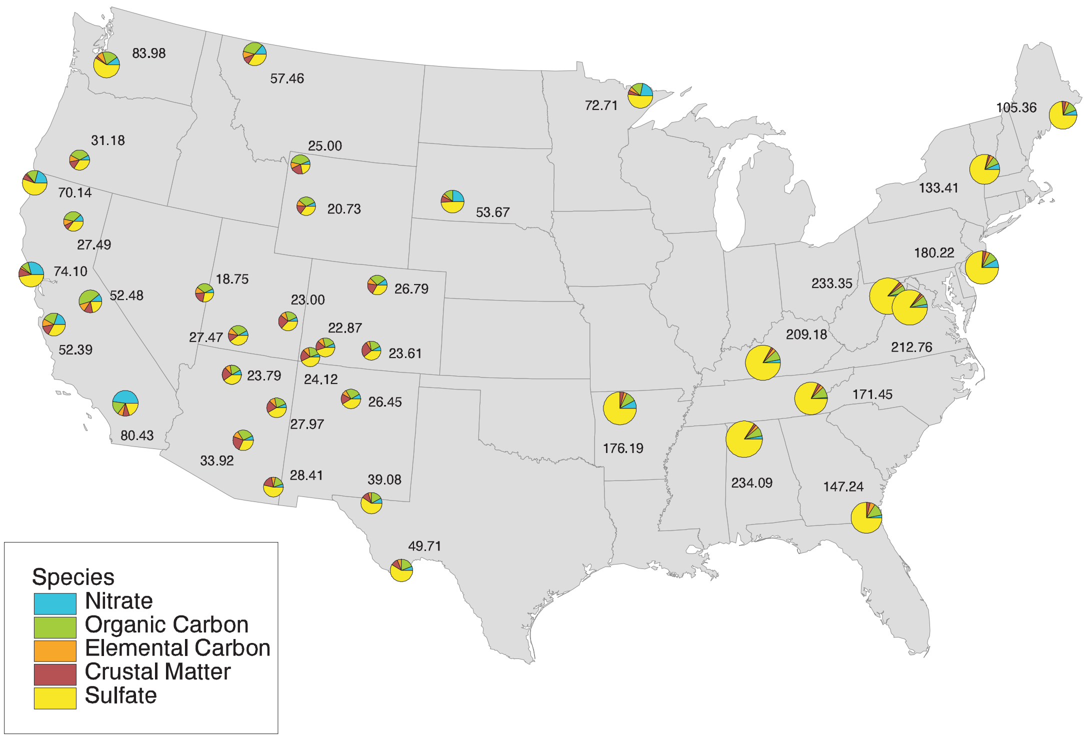


Figure 6-8a. Current visibility impairment expressed in deciviews for the clearest 20 percent days based on 1995–1997 IMPROVE data.

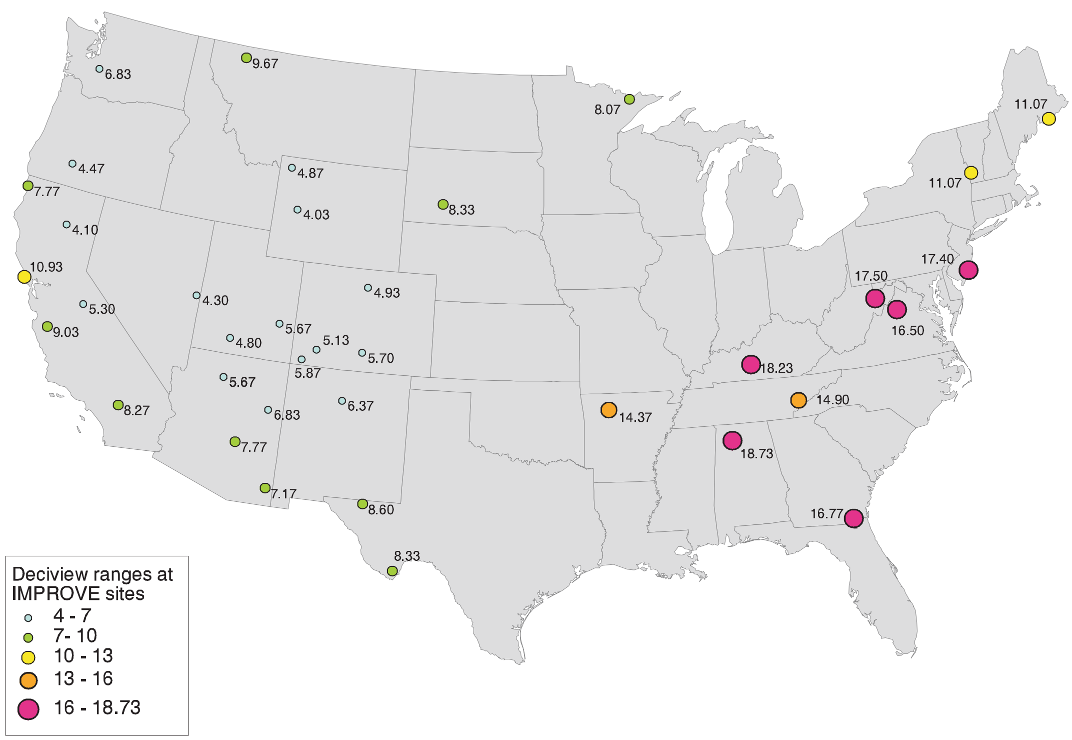


Figure 6-8b. Current visibility impairment expressed in deciviews for the middle 20 percent days based on 1995–1997 IMPROVE data.

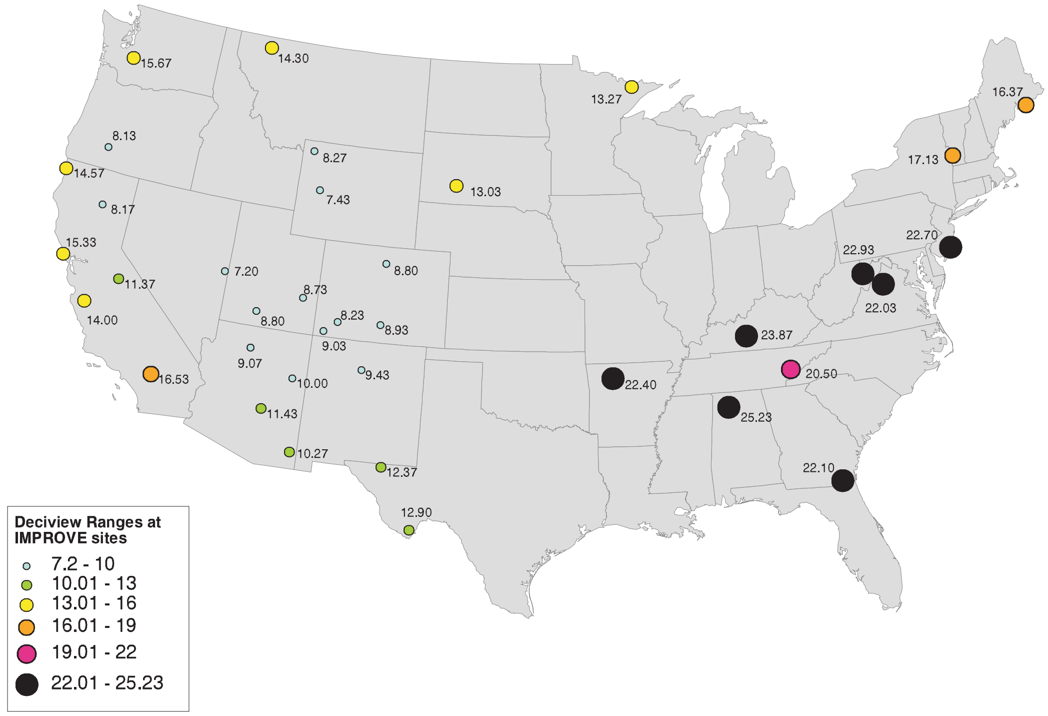
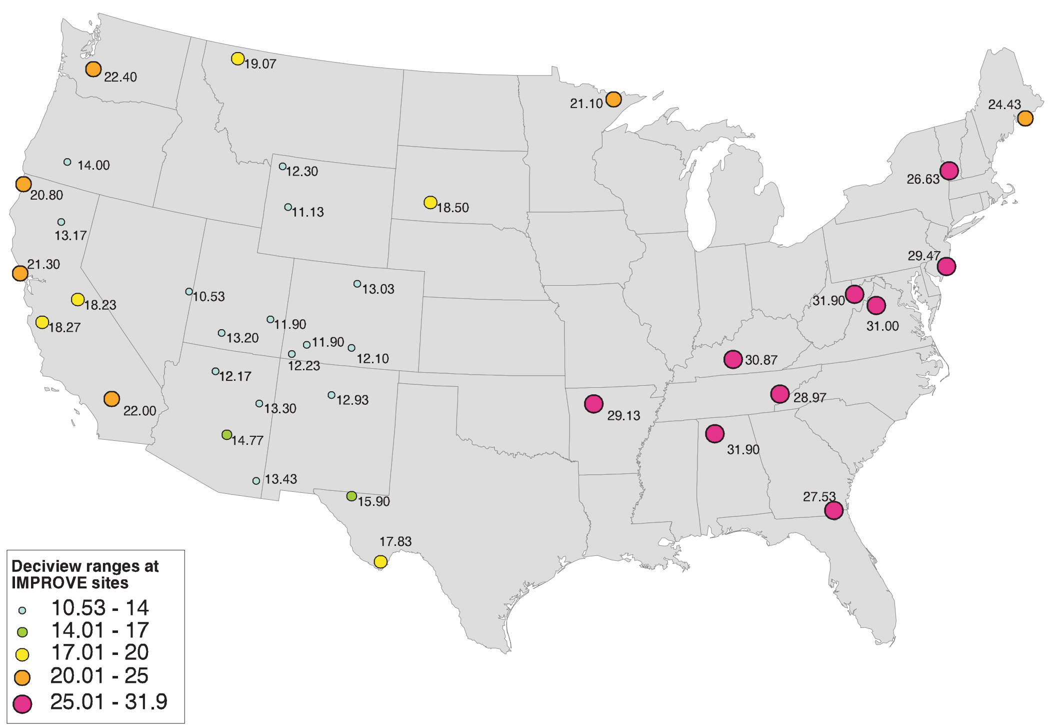


Figure 6-8c. Current visibility impairment expressed in deciviews for the haziest 20 percent days based on 1995–1997 IMPROVE data.



gional haze program. Another provision allows certain states until 2008 to develop coordinated strategies for regional haze and PM contingent upon future participation in regional planning groups.

Implementation of the PM and Ozone NAAQS in conjunction with a future regional haze program is expected to improve visibility in urban as well as rural areas across the country. Other air quality programs are expected to bring about emissions reductions that will improve visibility in certain regions of the country. The acid rain program will achieve significant regional reductions in the emissions of SO_2, which will reduce sulfate haze particularly in the eastern United States. When implemented, the NO_x State Implementation Plan (SIP) call to reduce emissions from sources of NOx to reduce formation of ozone should also improve regional visibility conditions to some degree. In addition, visibility impairment in class I areas should improve as a result of a number of other programs, including mobile source emissions and fuel standards, certain air toxics standards, and implementation of smoke management and woodstove programs to reduce fuel combustion and soot emissions.

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2. PhotoCD images provided by Kristi Savig and John Molenar, Air Resource Specialists, Inc., Fort Collins, Colorado 80525.

3. Sisler, J. *Spatial and Seasonal Patterns and Long-Term Variability of the Composition of the Haze in the United States: An Analysis of Data from the IMPROVE Network*. Colorado State University, Cooperative Institute for Research in the Atmosphere. Fort Collins, CO., 1996.

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5. R. B. Husar, J. B. Elkins, W.E . Wilson, "U.S. Visibility Trends, 1906–1992," Air and Waste Management Association 87th Annual Meeting and Exhibition, Cincinnati, OH, 1994.

6. See reference 1.

7. See reference 1.

8. The final regional haze rule was signed on 4/22/99 and published in the *Federal Register* on 7/1/99 (*64 Federal Register 35713*).